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DESIGN & SIMULATION OF A PRECISION ROTATING VALVE SYSTEM FOR NEUTRON IMAGING

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INTRODUCTION

The development of neutron imaging at Lawrence Livermore National Laboratory (LLNL) has lead to the development of various neutron generating devices. From rotating apertures, to pulse valve gas systems, to hard targets, all have worked by placing an interaction material in front of a deuteron beam to generate neutrons. The next generation of neutron generating devices will utilize a precision rotating gas valve system that will place a deuterium gas pulse in front of deuteron beam at a rate of 120Hz. As with the other neutron generating devices, it will be part of a larger system that will include a linear accelerator that creates the deuteron beam, a scintillator detector and high resolution CCD cameras.

SYSTEM DESIGN

The rotating valve design consists of a rotating valve encased in a pressure vessel as shown below in Figure 1. The valve is feed by intake and exhaust ports that carry deuterium and argon gases.
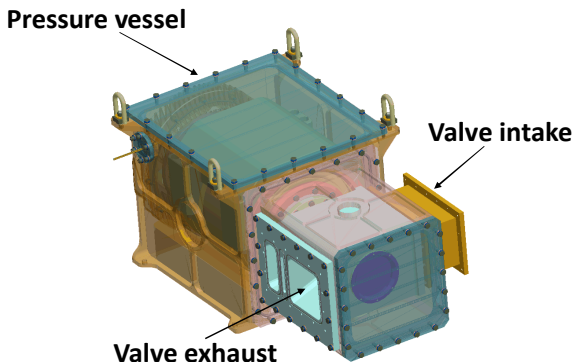

FIGURE 1. Rotary Valve in Pressure Vessel.

A cutaway of the front end of the valve is shown in Figure 2 with the rotary valve lined up with the intake and exhaust ports. This is the position in which the beam is fired through deuterium and argon chambers. The valve head rotates within

the valve housing with a targeted radial gap of 50 micron. This will limit leakage into the pressure vessel.
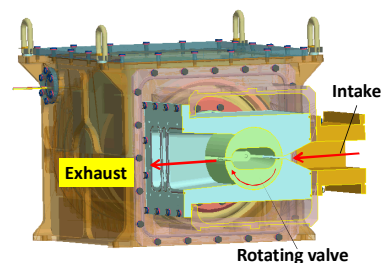

FIGURE 2. Cutaway of valve front end.

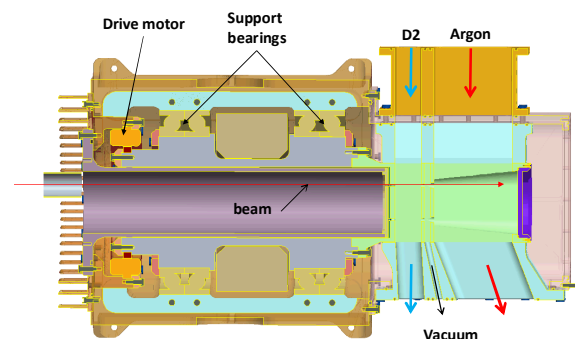A complete cutaway along the beam line is shown below in Figure 3.

FIGURE 3. Cutaway showing chambers.

Every half revolution the beam will fire through a vacuum beam line tube that runs between the support bearings and is ultimately connected to the deuteron linear accelerator. As the valve ports line up with the chambers, a shutter in the beam tube is uncovered to allow the beam to fire through from the beam tube and onto the valve chambers for 150 microseconds. The first chamber the beam enters is filled with deuterium (D2) at a pressure of 5 bar and the beam interaction with this gas leads to the creation of

neutrons. The beam next fires through to the intermediate chamber, which is held at a low pressure so as to reduce the mixing of D2 and argon in their respective chambers. The beam finally enters the beam stop chamber, where the beam interacts with argon at 5 bar and causes the beam energy to be dissipated into the moving argon gas.

SYSTEM MODELING

Modeling of the valve was done in two ways: first using a lumped parameter model and later using Ansys Fluent, which is a commercial Computational Fluid Dynamic (CFD) program with a moving mesh.

For the lumped modeling the valve was modeled as a rotating slot with the gas input through a venturi at the top as shown in Figure 4. The slot width is 6mm and as the slot lines up with the intake port, the gas flows through the chamber and out through the exhaust port.
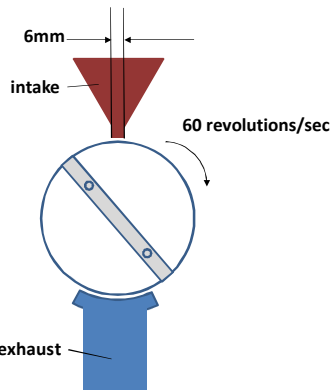

FIGURE 4. Simplified model of valve.

The rotating slot was modeled as a control volume with isentropic nozzles at either end for intake and exhaust as shown in Figure 5. The mass flow and enthalpy through the nozzles is described in equation 1 and 2 below [1]. The nozzle flow area, A(t) is the time varying area of the intake or exhaust ports and the flow was inviscid.

$$\dot{m} = A(t)\frac{P_u}{\sqrt{T_u}}\sqrt{\frac{2\gamma}{R(\gamma-1)}}\sqrt{Pr^{2/\gamma}-Pr^{(\gamma+1)/\gamma}} \qquad (1)$$

$$\dot{h} = C_pT_uA(t)\frac{P_u}{\sqrt{T_u}}\sqrt{\frac{2\gamma}{R(\gamma-1)}}\sqrt{Pr^{2/\gamma}-Pr^{(\gamma+1)/\gamma}} \qquad (2)$$

Where:

$\dot{m} = $ mass flow into or out of control volume

$\dot{h} = $ enthalpy flow into or out of control volume

$A(t) = $ flow area

$P_u = $ upstream pressure

$P_d = $ downstream pressure

$C_p = $ specific heat constant pressure

$C_v = $ specific heat constant volume

$$Pr = \frac{P_d}{P_u} \qquad \gamma = \frac{C_p}{C_v} \qquad R = C_p - C_v$$
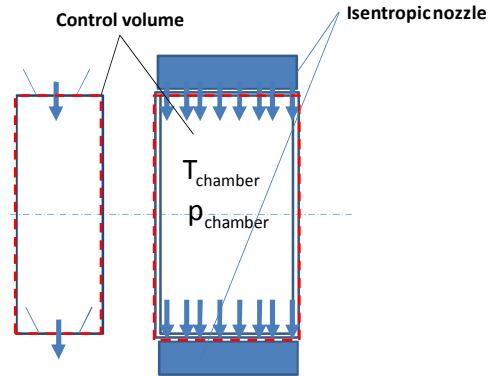

FIGURE 5. Side view of control volume.

The energy in the control volume, (cv) is calculated as changes in temperature due to the beam power in the control volume and the flow of the gas enthalpies in and out as shown below in equation (3):

$$\frac{dT_{cv}}{dt} = \frac{q + \left[\dot{h}_{in}(T_{cv}) - \dot{h}_{out}(T_{cv})\right]}{(m_{in} - m_{out})c_v} \qquad (3)$$

Where:

$q = $ beam power into control volume

$T_{cv} = $ temperature of control volume

The beam power represents the heat output of the reaction between the deuteron beam and the gas. The pressure in the control volume is then calculated from the ideal gas law applied to the control volume as shown below in equation (4):

$$P_{cv} = \frac{m_{cv}RT_{cv}}{V_{cv}} \qquad (4)$$

The complete dynamic model represented by equations 1 through 4 was simulated using helium in lieu of deuterium gas. Helium has similar density to deuterium but different heat capacities. For the initial experiments helium will be used in-lieu of deuterium because it's not an explosive gas. Once the rotary valve system has been shown to work with helium, it would be placed in front of a linear accelerator with deuterium and argon gas sources.

The simulated pressure pulse inside the control volume is shown in Figure 6, with a 5 atmosphere helium gas source. Also shown is the rotating valve intake area as a function of time, thus showing the delay between the maximum valve opening and the peak pressure pulse.
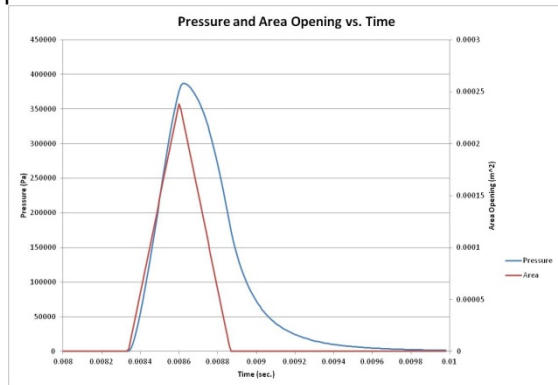

FIGURE 6. Pressure pulse simulation.

The rotary valve was also modeled using Ansys's Fluent CFD software with a moving mesh to simulate the rotation of the slot past the intake and exhaust ports as shown in Figure 7.
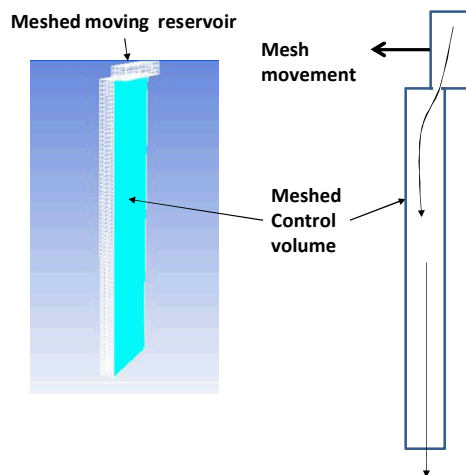

FIGURE 7. Ansys moving mesh model

The CFD model was initially run with helium under inviscid flow as way to compare it with the analytical lumped parameter model. Both models compared well with each other as shown below in Figure 8. When the more realistic condition of viscous flow was implemented deviations were seen as shown in the last 2 columns. With viscous flow comes a boundary layer that narrows the flow path through the slot, increases pressure and velocity, which leads to further expansion of the gas as it exhaust and causes a cooling of the gas. These results are what are expected when the rotary valve is operated with helium.

Boundary Condition: 500 kPa inlet pressure, 30kPa outlet pressure, no power

	Analytical	CFD Inviscid Flow	CFD	% Difference
Upper Pressure	388,000 Pa peak	369,000 Pa	431,000 Pa Beam line	11%
Upper Temperature	332 K peak	362 K	257K beam line	-22%
Density at beam	0.48 Kg/m^3 Inferred From NIST table	0.49 Kg/m^3	0.58 Kg/m^3	~21 %
Upper velocity beam	*570 m/s	525 m/s	754 m/s	32%

*inviscid flow

FIGURE 8. Table comparing different simulation results for helium gas at 5 atmospheres

The goal of the rotary valve is to place helium (deuterium for actual imaging) in front of the beam with sufficient density so that the beam interaction will produce neutrons. The minimum density required for that is 0.48 Kg/m^3. The CFD simulation of the density at top dead center shows that at the beam line the predicted density will be 0.63. Kg/m^3 as shown below in Figure 9.
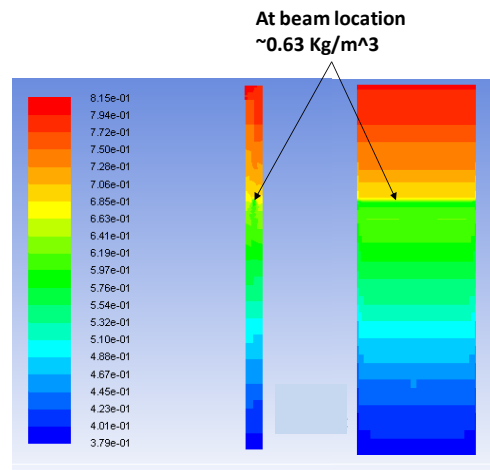

FIGURE 9. Helium density in control volume.

LEAKAGE & ERROR BUDGET

The above simulations do not account for the leakage between the rotating rotary valve head and the valve head body as shown in Figure 10. The leakage represents an additional amount of gas that will need to be added to the intake flow into the rotary valve.
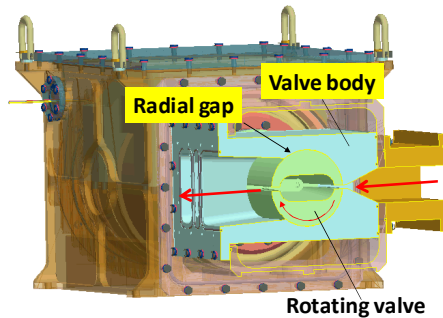

FIGURE 10. Leakage between rotating valve and valve body.

This leakage has been modeled using CFD and approximated using a simple isentropic nozzle model. These simulations track well together and with the area of the leakage as shown below in Figure 11 for a range of radial gaps.
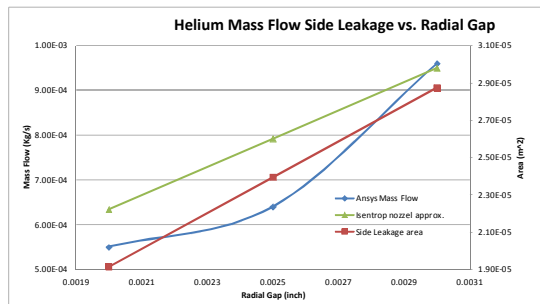

FIGURE 11. Simulations of leakage out the side of the valve as a function of radial gap.

Leakages from all sources can easily double the total mass flow needed to achieve the desired gas densities in the slot. This will increase the cost of the gas handling system. Reducing the leakage requires the radial gap to be a small as possible given fabrication constraints.

An error budget was created to estimate the possible radial gaps that could be achieved using precision machining methods as shown in Figure 12. The sources of potential error include bearing run out, the support of the bearings outside diameter, rotary valve location on the main shaft, rotary valve run out, main shaft

bearing surface misalignment and the tilting of the rotor due to the perpendicularity tolerance between the rotor mounting flange and the axis of rotation. In addition to the fabrication errors, the change in the radial gap due to the thermal expansion of the rotary valve was estimated using a Finite element model of the rotary valve. The boundary conditions for the model included the cooling effect of the deuterium and argon gases. The heat source was the heat generated by the argon as it stops the beam, which is estimated to be 109kW for 150 microseconds.

Error Source	Radial Direction (um)	type
Brg. run out	9.11	p-v
Brg. O.D. support	14.12	p-v
Rotor housing	5.08	p-v
Rotor valve run out	6.35	p-v
Shaft mis-alignment	19.10	p-v
Tilt at rotor	42.95	
Thermal expansion	2.7	p-v
sum	99.40	p-v
RMS of p-v	14.64	p-v
Total (sum+RMS)/2	57.02	p-v

FIGURE 12. Error budget for valve's radial gap.

The total error estimated using the average of the sum plus RSS errors was 57 microns [2]. This exceeds the targeted radial gap shown in the simulation of 50 microns. The error budget indicates that improvements in the tilt error and shaft misalignment tolerances could significantly reduce the estimated radial gap error.

REFERENCES

[1] Karnopp, D.C., Margolis, D.L., Rosenberg, R.C. System Dynamics, A Unified Approach, 2nd Ed, John Wyle & Sons, Inc: 1990.

[2] Shen, Y.L., Duffie, N.A., Comparison of Combinatory Rules for Machine Error Budgets, Annals of CIRP, Vol. 42, No. 1, 1993.